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Wave-theory modelling of convergence zone propagation in the ocean

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Wave-theory modelling of convergence zone propagation in the ocean

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Abstract: Improved numerical techniques together with continual advances in computer technology have now made it feasible to study sound propagation in the deep ocean with wave-theory models and hence avoid the artefacts and approximations associated with standard ray-theory analysis techniques. We apply a computationally efficient normal-mode code to the problem of convergence zone propagation, which is the repetitive focusing of sound (every 40–60 km) in the upper part of the ocean for an acoustic source near the sea surface. In the study we investigate the structure of the first 3 convergence zones as a function of geographical area (Mediterranean and Atlantic), season (summer and winter), frequency (25–200 Hz), and source/receiver depth (15–300 m). It is shown that convergence-zone propagation only occurs under summer conditions, and that the focusing of sound is much stronger in the Atlantic than in the Mediterranean. Moreover the convergence zone length is around 60 km in the Atlantic and just 35–40 km in the Mediterranean.

Keywords: Atlantic ○ convergence zone propagation ○ Mediterranean ○ SUPERSNAP ○ wave-theory modelling

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1. Introduction

Convergence zone propagation is a phenomenon dealt with in most text-books on underwater acoustics [1,2]. It is associated with propagation in deep water from a source that is near the sea surface and also within a negative sound-speed gradient layer. Under these circumstances the emitted sound (up- and down-going) within small angles from the horizontal forms a downward-directed beam, which will follow a deep refracted path and reappear near the surface at a distance of tens of kilometres from the source. The phenomenon is repetitive, resulting in high sound intensity near the sea surface (a convergence zone) at range intervals called the convergence zone length. An illustrative example is given in Fig. I-1a.

The importance of convergence zone propagation stems from the fact that it allows for long-range transmission of acoustic signals of high intensity and low distortion. The first reference to convergence zone propagation in the open literature goes back 25 years to a now classical paper by Hale [3]. He reported experimental data covering a range of almost 750 km and clearly showing 13 distinct convergence zones spaced approximately 55 km apart. Hale [3] also addressed in some detail the environmental conditions for the existence of convergence zones and attempted a theoretical description of the convergence zone structure using ray theory. He concluded, however, that for an accurate modelling of the acoustic field in a convergence zone, a wave theory approach was needed, and he briefly alluded to the possibility of using normal modes.

In a paper from 1974, Guthrie et al. [4] reported on the frequency dependence of convergence zone spacing in the North Atlantic. In their experiment, covering a range of 3000 km, 37 convergence zones were identified for a 14-Hz source, while approximately half that number of zones were identified for a 111-Hz source. The observed distance between convergence zones was 62 km at 14 Hz and 65 km at 111 Hz, a feature which was shown to agree with theoretical predictions obtained with a normal-mode model.

More recently Hanna and Rost [5] published convergence zone data from the North Pacific covering a range of 950 km. As many as 17 convergence zones were observed with an average spacing of 55 km. Since propagation here was through a range-dependent environment, the modelling was done with the parabolic equation. Good agreement was obtained between data and model predictions for a variety of source/receiver combinations and for frequencies between 25 and 100 Hz.

By the early 80s advances in computer technology finally permitted wave-theory simulations of convergence zone propagation on a broader scale, and we find two modelling papers on this subject, both dated 1983 [6,7]. Henrick and Burkom [6] studied the effect of range dependence on convergence zone propagation using a parabolic equation model, while Beilis [7] investigated a hybrid ray-mode approach for determining convergence zone positions.

The scope of the present document is twofold: Firstly to demonstrate that normal-mode modelling of deep water propagation has now become practical even for frequencies where hundreds of modes must be computed and summed to evaluate the acoustic field. Secondly to illustrate the major differences between convergence zone propagation in the Mediterranean and the Eastern North Atlantic, two areas for which experimental data are extremely sparse.

The acoustic model employed in this study is the latest version of our normal mode model SUPERSNAP [8] which was recently upgraded by replacing the central modal eigenvalue routine by a fast solver proposed by Porter and Riess [9], a change which resulted in an order-of-magnitude speed gain in generating a modal field. With this model we can compute the convergence zone structure in 4500 m of water and at 200 Hz in just 10 min on a VAX 8600, even though the field is composed of approximately 200 modes.

For the convergence zone study we have selected representative sound-speed profiles from the Mediterranean and the Atlantic for both summer and winter. We have chosen a frequency range of 25–200 Hz, and have selected a number of source/receiver positions in the upper 300 m of the water column. This set of input parameters allow us to investigate the convergence zone structure as a function of geographical area, season, frequency, and source/receiver depth.

2. The acoustic model

Normal-mode theory has been extensively used for more than a decade to describe ducted propagation in the ocean. Since the early 70s when most laboratories got access to good computing facilities, several propagation models based on normal modes have been developed, among those the SNAP model [8]. The earlier use of these models was restricted to situations involving few modes, i.e. shallow water at low and intermediate frequencies, and deep water at very low frequencies. Essentially only a few tens of modes could be calculated for practical reasons.

Today with faster computers and with the implementation of rapidly converging numerical schemes, normal-mode models have become practical even for situations involving hundreds of modes. Thus with the latest version of the SNAP model we can compute 100 modes in deep water in a couple of minutes on a VAX 8600.

The SNAP model is designed to give a realistic treatment of the ocean environment, which is divided into three layers: water, sediment and subbottom. Environmental inputs to the model are:

- Arbitrary sound-speed profile in the water column.
- Density, attenuation and sound-speed profile of the sediment layer.

- Density, shear speed, compressional speed, shear attenuation, and compressional attenuation of the homogeneous subbottom.
- RMS roughness of sea surface and sea floor.

Furthermore the model treats range dependence in the adiabatic approximation. In this case the environmental inputs listed above may vary arbitrarily with range. However, accurate field solutions can be expected only when the coupling of energy between modes is negligible, i.e. for weak range dependence.

A significant improvement in computational speed was obtained recently by replacing the central modal eigenvalue routine by a fast solver proposed by Porter and Riess [9]. This change resulted in an order-of-magnitude speed gain in generating a modal field, and, in addition, removed some numerical stability problems inherent in the original SNAP code. This recent version of the code (SUPERSNAP) is also fully automated, i.e. there are no numerical parameters to be determined by the user.

In terms of computational speed, performance reliability and automation, a normal-mode model is superior to any other wave-theory model in use today, and SUPERSNAP therefore was the natural choice for the present convergence zone study. Practical limitations, however, still persist. In the present study we compute convergence zone structures in 4500 m of water at frequencies up to 200 Hz within 10 min on a VAX 8600. However, with the computation time being proportional to frequency squared, a 1 kHz calculation would require approximately 4 h, which is clearly both impractical and costly. Hence the application of wave-theory models to deep water propagation is in practice limited to frequencies below a few hundred Hertz.

3. Environmental inputs and organisation of sample outputs

Representative sound-speed profiles for the Atlantic and the Mediterranean in summer and winter are given in Fig. 1. The water depth is 2500 m in the Mediterranean and 4500 m in the Atlantic. The Atlantic double-duct profile is characteristic of the Eastern North Atlantic, where we have mixing of cold Atlantic water with warm Mediterranean water flowing out through the Strait of Gibraltar. In the upper 500 m of the ocean the Atlantic and Mediterranean profiles are very similar, as shown explicitly in Fig. 2. The higher speed of 10–15 m/s in the Mediterranean is due both to higher mean temperature and higher salinity. However for both profiles there is a duct at the surface in winter and a duct at 150 m depth in summer. These profile features will generally result in ducted propagation in winter, and also in summer for a source close to the sound channel axis (150 m).

Since convergence zone propagation is associated with deep refracted paths in the ocean, we wish to eliminate bottom interacting paths. This is most conveniently done by introducing a non-reflecting bottom in the model, which is a halfspace with the properties of the water just above the bottom. Thus we associate with the bottom a constant speed equal to the speed at the bottom of the water column, a density of 1 g/cm^3 and zero attenuation. By doing so we ensure that only waterborne energy is included in the modal solution.

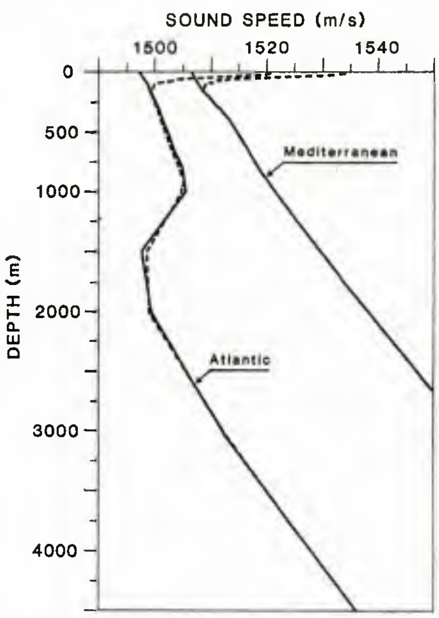

Fig. 1: Representative profiles for the North Atlantic and the Mediterranean for summer (dashed curves) and winter (solid curves).

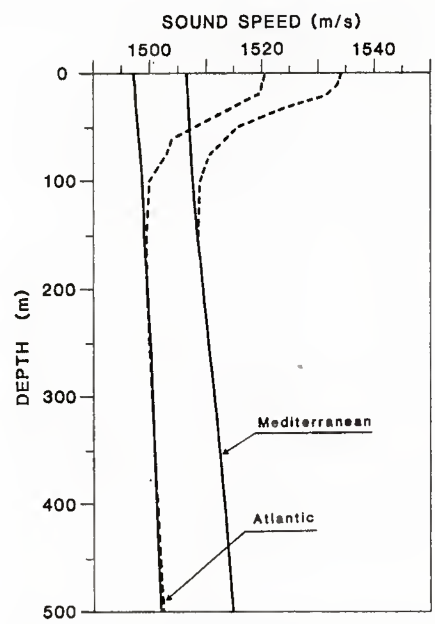

Fig. 2: Expanded view of the profile differences near the sea surface for summer (dashed curves) and winter (solid curves).

We will be investigating the first 3 convergence zones for frequencies between 25 and 200 Hz and for a selected number of source/receiver positions in the upper 300 m of the water column. Since the choice of studying 2 geographical areas, in 2 different seasons, for 4 different frequencies, and for 8 different source/receiver depth combinations implies a total of 128 transmission loss curves, it is important to organize the output in a systematic manner. We have chosen to present the results in four groups of figures:

I. Contoured transmission loss versus depth and range illustrating the general features of convergence propagation in the Mediterranean and the Atlantic.

II. Transmission loss versus range illustrating the frequency dependence of convergence zone structures.

III. Transmission loss versus range illustrating the dependence of convergence zone structures on source/receiver position.

IV. Transmission loss versus range illustrating the seasonal and areal dependence of convergence zone structures.

> Geometrical spreading $10 \log r$ (with range in metres) has been removed from all displays. The reason for removing cylindrical spreading from the displays is primarily to be able to produce ray-like pictures of convergence zone propagation as seen in the contour plots in Figs. I-1,2. However, also the individual transmission loss curves can be displayed in a more compact form when the geometrical spreading is removed.

4. General features of convergence zone propagation

Necessary conditions for the formation of convergence zones are that the source is near the surface and that the profile is downward-refracting in the vicinity of the source. Moreover in order to avoid that the deep refracted paths interact with the bottom, the ocean must be deep enough that the sound speed near the bottom is higher than at the source (depth excess). Thus we should not expect convergence zone propagation in winter, where the profile is upward-refracting (see Fig. 2), and neither in summer for water depths less than 2000 m in the Mediterranean and 3500 m in the Atlantic, in which cases we would be bottom-limited for a near-surface source.

When convergence zone propagation occurs the emitted sound from the source (up- and down-going) within small angles from the horizontal forms a downward-directed beam which will follow a deep refracted path in the ocean and reappear near the surface at a distance of 40–60 km from the source. The phenomenon is repetitive, resulting in high sound intensity near the sea surface (a convergence zone) at range intervals called the convergence zone length.

- *Atlantic* An illustrative example for the Atlantic in *summer* is shown in Fig. I-1a. Here we have contoured the high intensity part (upper 6 dB) of the acoustic field in 2 dB intervals, with cylindrical spreading removed. We see a classical convergence zone pattern, with a distance between the zones of approximately 60 km. Note that the width of the convergence zones increases with zone number; the second zone (near 120 km) is wider than the first, and so on, until eventually the zones overlap and become indistinguishable. Since the result in Fig. I-1a is generated by wave theory, the field intensity is finite everywhere, also in the shadow zones. In fact, if we increased the contour interval we would see that the shadow zone levels are approximately 45 dB below the convergence zone levels.

  Figure I-1b gives the equivalent result for the Atlantic in *winter*. Since the winter profile allows for ducted propagation near the surface, convergence zone paths are here of minor importance. Notice the presence of deep caustics around a depth of 2500 m.

- *Mediterranean* When looking at the result for the Mediterranean in *summer* (Fig. I-2a) we see again a characteristic convergence zone pattern, however here with the zones spaced only 40 km apart. Moreover the convergence zones in the Mediterranean are much wider than in the Atlantic. By increasing the contour interval we would see that the shadow zone levels are approximately 30 dB below the convergence zone levels.

> Finally the result for the Mediterranean in *winter* (Fig. I-2b) shows that propagation is dominated by ducting near the surface, and we again notice some interesting caustic features in the deep ocean.

Summarising, it is evident from the contour plots of Figs. I-1 and I-2 that convergence zone paths are important only under summer conditions, that the convergence zone spacing is longer in the Atlantic (60 km) than in the Mediterranean (40 km), that the convergence zones are much narrower in the Atlantic than in the Mediterranean, and that the convergence zone width increases with zone number. A more detailed analysis of the model results will be given in the following section.

We should like to address one more aspect of convergence zone propagation, the convergence gain, which is a measure of the degree of focusing of sound in a convergence zone. The convergence gain has arbitrarily been defined as the peak intensity in a convergence zone relative to the level corresponding to spherical spreading plus absorption. This seems an inappropriate definition, since the geometrical spreading law that applies to long-range ducted propagation is cylindrical spreading. However, using the standard definition, Urick [1] states that convergence gains are generally 10–15 dB, but that values as high as 25 dB have been recorded.

Our predicted convergence gain for the Atlantic summer profile at 200 Hz can be read off the lowermost curve in Fig. II-1a, where the loss corresponding to spherical spreading is displayed. We see that the convergence gain is high in the Atlantic, being around 26 dB in the first convergence zone and increasing to 30 dB in the third zone. Results for the Mediterranean in summer at 200 Hz is given in the lowermost curve of Fig. II-3a. Here the convergence gain is smaller, being around 18 dB in the first three zones.

Finally we briefly reiterate the question of the convergence zone width, which we found to be different in the two ocean areas considered. Urick [1] states that the convergence zone width is around 5–10% of the convergence zone spacing, which for the Atlantic should give a width of 3–6 km, and for the Mediterranean a width of just 2–4 km. Urick, however, does not specify how the convergence zone width should be measured. If we return to the lower curve in Fig. II-1a for the Atlantic in summer, we see that the width of the first zone is around 5 km when measured at the level corresponding to spherical spreading. This value agrees well with Urick's indication. However, our value for the width of the first zone in the Mediterranean (Fig. II-3a) is 12 km, measured at the level corresponding to spherical spreading. This value is 30% of the convergence zone spacing, and a much higher value than indicated by Urick. Considering furthermore that the zone width increases strongly with zone number and also with receiver depth, it is hardly meaningful to give average numbers for the convergence zone width relative to the convergence zone spacing.

5. Detailed analysis of convergence zone structures

In this section we present a detailed comparison of convergence zones in the Mediterranean and the Atlantic with emphasis on frequency dependence, source/receiver depth dependence, and seasonal dependence. It is once more recalled that all transmission loss curves are displayed without cylindrical spreading loss ($10 \log r$).

5.1. FREQUENCY DEPENDENCE

Figures II-1 to II-4 illustrate the frequency dependence of convergence zones for selected source/receiver depths.

- *Atlantic* Starting with propagation in the Atlantic in *summer* (Fig. II-1), we notice that there is a considerable sharpening of the convergence zones with increasing frequency, resulting in a change in convergence gain from around 0 dB at 25 Hz to approximately 26 dB at 200 Hz. Also the multipath interference structure within the shadow zones partly disappears with increasing frequency. The convergence zone length is seen to be virtually independent of frequency and equal to 60.5 km. For a deep source at 100 m depth (Fig. II-1c) significant convergence zone structure is seen only at 25 Hz. At higher frequencies the propagation becomes ducted in the shallow sound channel.

  Propagation in the Atlantic in *winter* (Fig. II-2) is dominated by ducting near the surface, except at the lowest frequencies. For a shallow source and receiver (Fig. II-2a) we can identify the first three convergence zones up to a frequency of 100 Hz, while for a deep source and receiver (Fig. II-2c) the convergence zones are noticeable only at 25 Hz.

- *Mediterranean* In the Mediterranean in *summer* (Fig. II-3) convergence zones are just barely visible at low frequencies; only at 200 Hz and for a shallow source and receiver are the first three convergence zones well separated. The convergence zone spacing is here clearly frequency dependent, being around 38 km at 25 Hz and increasing to 40.5 km at 200 Hz. This change in convergence zone length of 2.5 km is a result similar to that reported by Guthrie et al. [4] for the Western North Atlantic. They measured a change in convergence zone spacing of 3 km when changing the frequency from 14 to 111 Hz.

  The Mediterranean in *winter* (Fig. II-4) is totally dominated by ducted propagation near the sea surface.

5.2. SOURCE/RECEIVER DEPTH DEPENDENCE

Figures III-1 and III-2 show the dependence of convergence zone structures on source/receiver depth. The calculations have been done with a fixed source at 15 m depth and with the receiver varying in depth between 15 and 300 m. Invoking the

principle of reciprocity these results can also be interpreted as being for a fixed receiver at 15 m depth and for a source at depths between 15 and 300 m.

- *Atlantic* For the Atlantic in *summer* (Figs. III-1a,b) there is little depth dependence at 25 Hz while the convergence zones clearly widens with depth at 200 Hz, creating a double-peak structure for the deeper receivers. The convergence gain is seen to decrease with increasing distance from the sea surface.

  For the Atlantic in *winter* (Figs. III-1c,d) there is generally little depth dependence.

- *Mediterranean* The Mediterranean in *summer* (Figs. III-2a,b) is characterised by weak depth dependence of the acoustic field at 25 Hz, while there is considerable dependence on receiver depth at 200 Hz. Thus we see that the convergence zones widen and start overlapping as we move away from the sea surface.

  The Mediterranean in *winter* (Figs. III-2c,d) is dominated by ducted propagation, and there is negligible depth dependence.

5.3. SEASONAL DEPENDENCE

Both seasonal and areal dependence is illustrated in Figs. IV-1 and IV-2 for selected frequencies and source/receiver depth combinations. At a frequency of 25 Hz (Fig. IV-1) there are only minor differences between propagation in summer and winter. However, at 200 Hz (Fig. IV-2) the seasonal dependence is strong, especially for a shallow source and receiver. Figure IV-2a shows the change from convergence zone propagation in summer, with repetitive focusing of sound near the surface, to ducted propagation in winter, with almost constant insonification versus range. For a deep source and receiver at 200 Hz (Fig. IV-2c) we have ducted propagation in both summer and winter, and consequently the seasonal dependence is small.

5.4. AREAL DEPENDENCE

Propagation in the Atlantic is characteristically different from propagation in the Mediterranean, as explicitly shown in Figs. IV-1 and IV-2. The low-frequency results (25 Hz) given in Fig. IV-1 show convergence zone propagation in the Atlantic with clear focusing around 60 and 120 km. The convergence zone level is always 10–20 dB higher than the shadow zone level for the source/receiver depth combinations considered. In the Mediterranean, on the other hand, we have essentially ducted propagation at 25 Hz with constant insonification versus range.

At higher frequencies (Fig. IV-2) the winter results show no areal dependence, while the summer results are distinctly different in the two areas considered. As an

illustrative example we shall look at the upper curves in Fig. IV-2a, showing convergence zone propagation from a shallow source to a shallow receiver at 200 Hz. We have earlier pointed out the major differences between convergence zone structures in the Atlantic and the Mediterranean, but they shall here be briefly summarised. The convergence zone length in the Atlantic is around 60 km while it is 30% shorter in the Mediterranean (40 km). This means that the spatial position of the second convergence zone in the Atlantic coincides with the position of the third zone in the Mediterranean. Moreover the convergence zones are sharper and narrower in the Atlantic, resulting in good zone separation out to considerable ranges. In the Mediterranean only a few zones are distinguishable, as is evident from Fig. IV-2a.

6. Summary and conclusions

We have used a wave-theory model to study convergence zone propagation in the Atlantic and the Mediterranean. It was found that convergence zone paths are important only under summer conditions, that the convergence zone spacing is longer in the Atlantic (60 km) than in the Mediterranean (40 km), and that the convergence zones are much narrower in the Atlantic than in the Mediterranean. Moreover, we have presented model results showing in detail the dependence of convergence zone structures on frequency (25–200 Hz) and on source/receiver position within the upper 300 m of the ocean.

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Presentation of results:

Figures I – IV

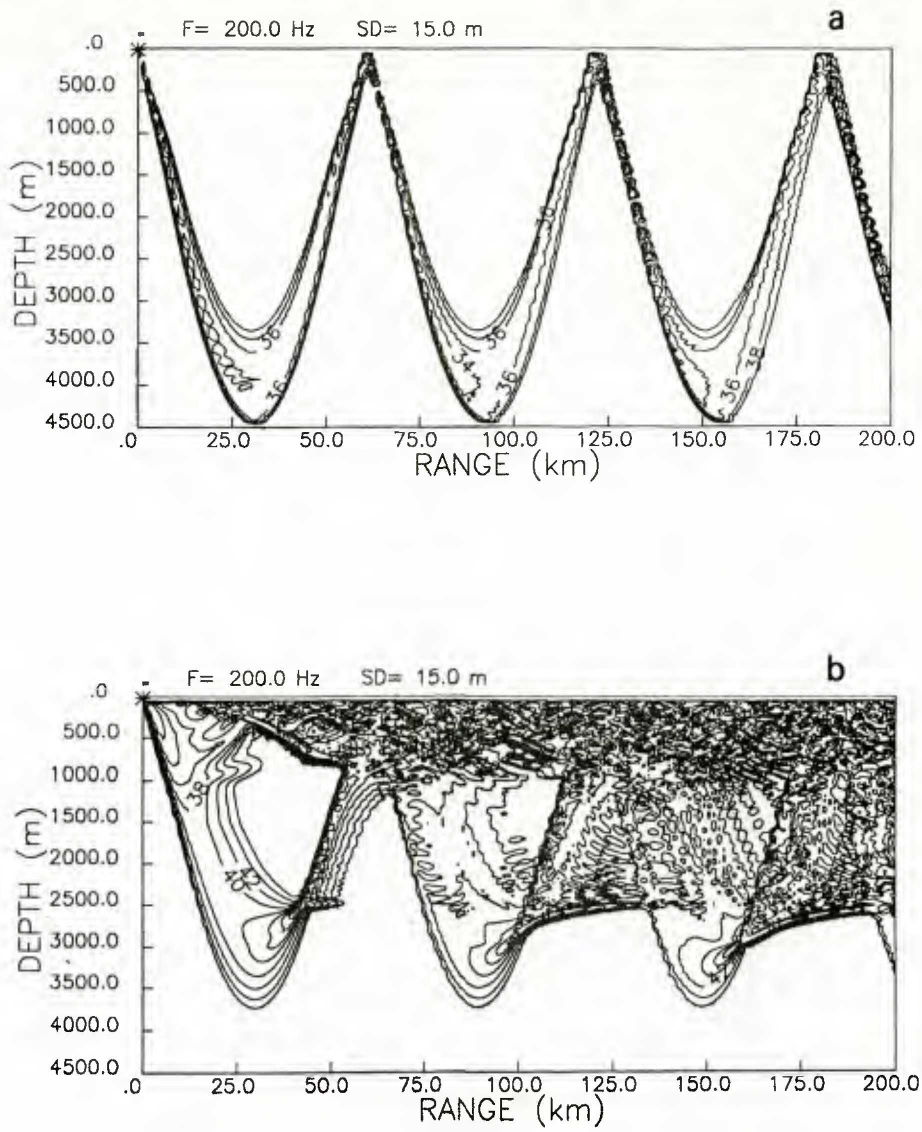

Fig. I-1: Contoured transmission loss versus depth and range for Atlantic profiles at F = 200 Hz, SD = 15 m: (a) summer; (b) winter.

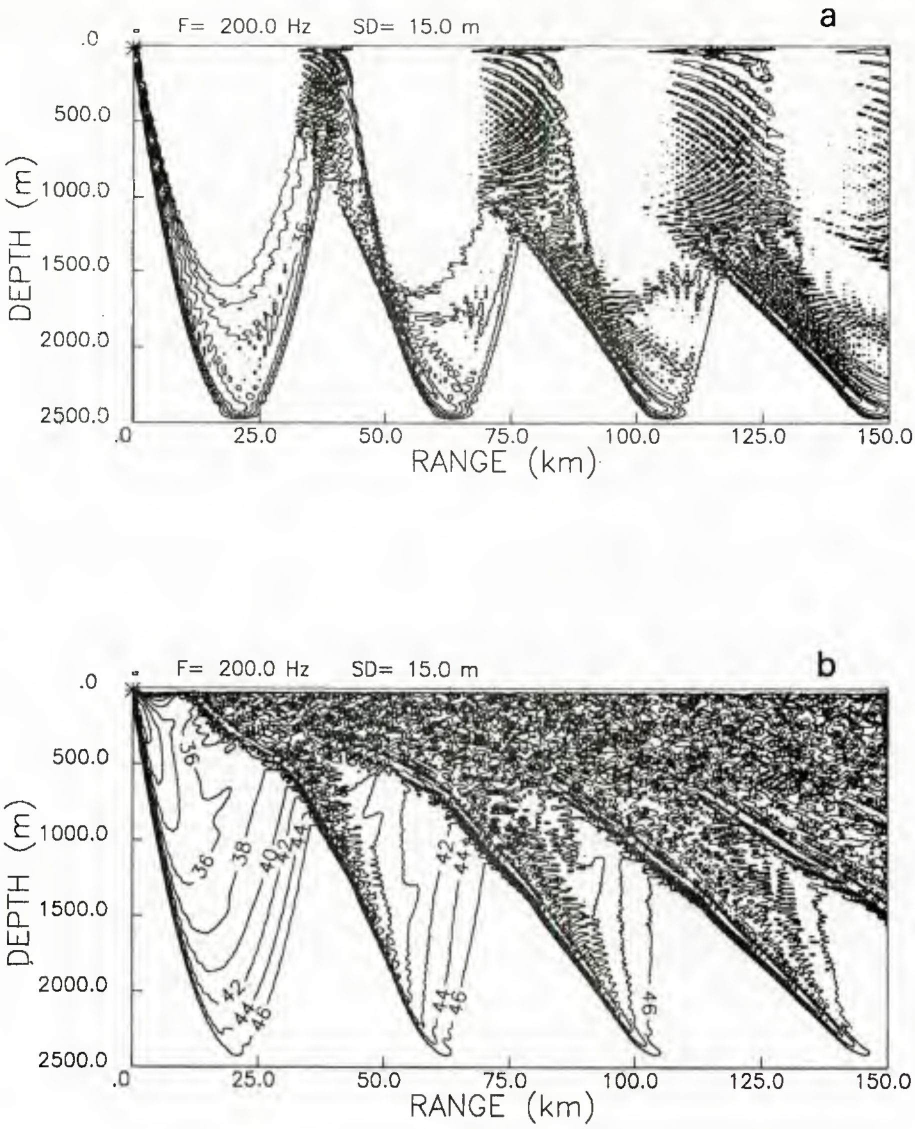

Fig. I-2: **Contoured transmission loss versus depth and range for Mediterranean profiles at $F = 200$ Hz, SD = 15 m: (a) summer; (b) winter.**

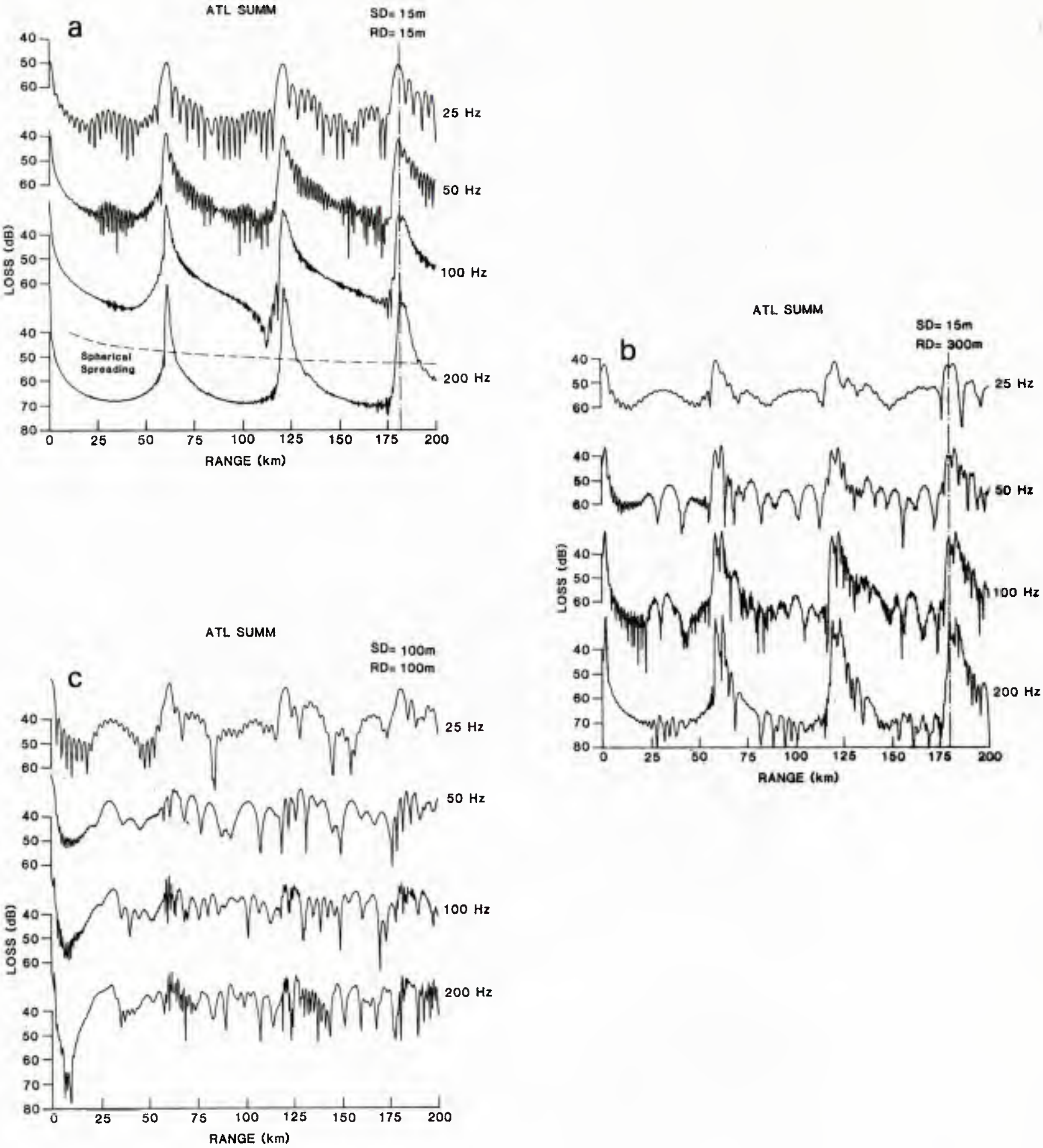

Fig. II-1: Transmission loss versus range at selected frequencies for Atlantic summer profile: (a) SD = 15 m, RD = 15 m; (b) SD = 15 m, RD = 300 m; (c) SD = 100 m, RD = 100 m.

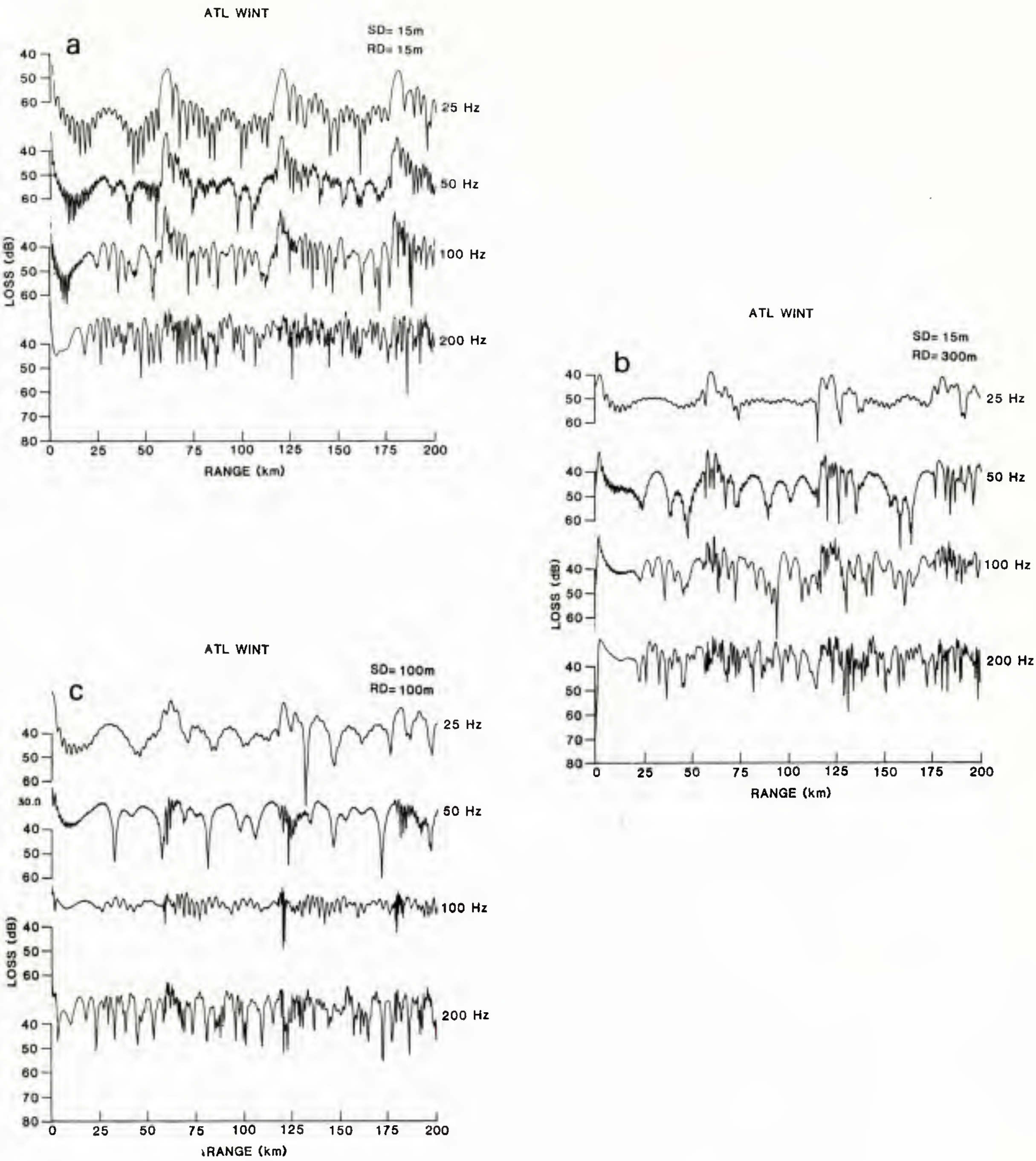

Fig. II-2: Transmission loss versus range at selected frequencies for Atlantic winter profile: (a) SD = 15 m, RD = 15 m; (b) SD = 15 m, RD = 300 m; (c) SD = 100 m, RD = 100 m.

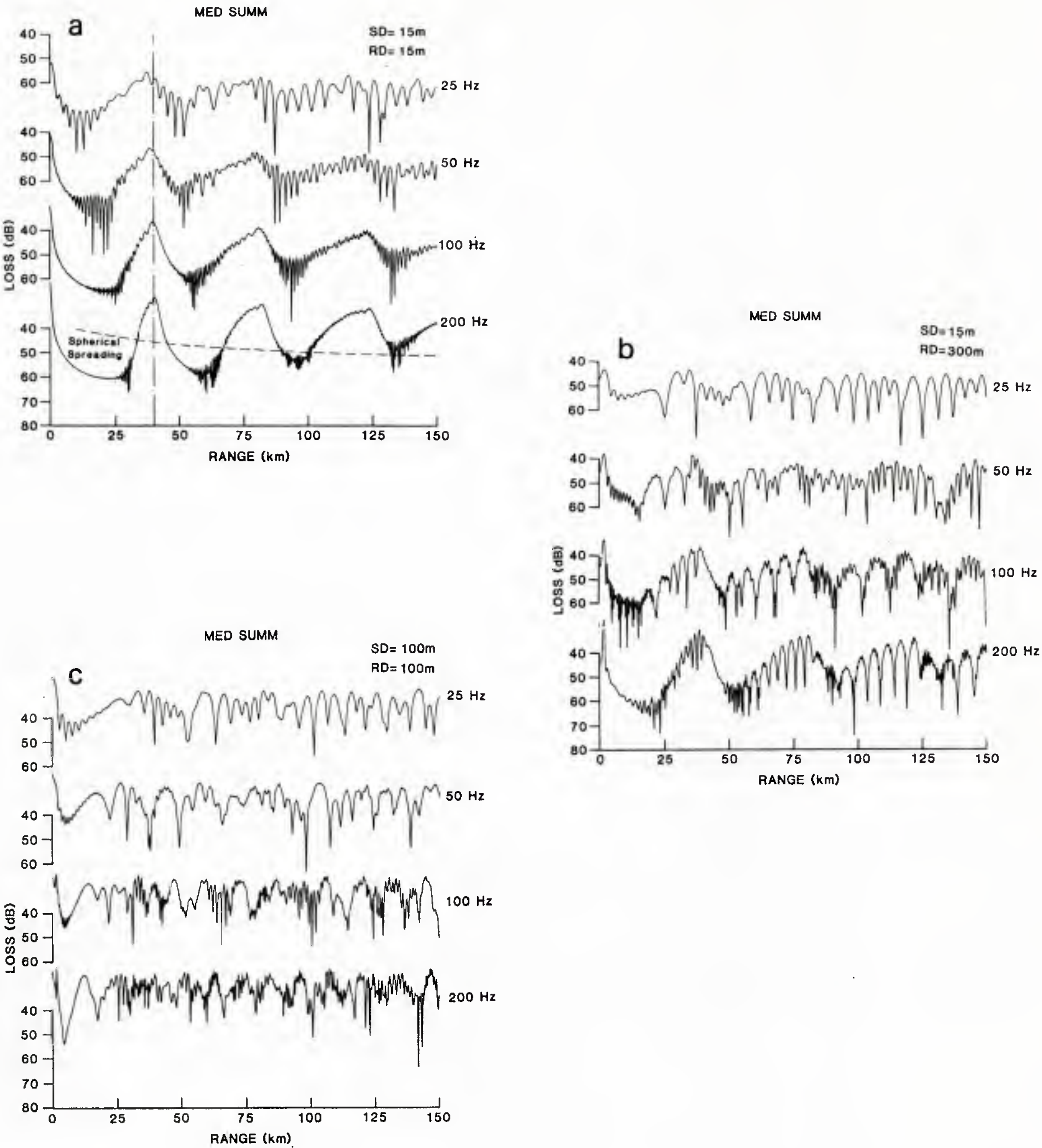

Fig. II-3: Transmission loss versus range at selected frequencies for Mediterranean summer profile: (a) SD = 15 m, RD = 15 m; (b) SD = 15 m, RD = 300 m; (c) SD = 100 m, RD = 100 m.

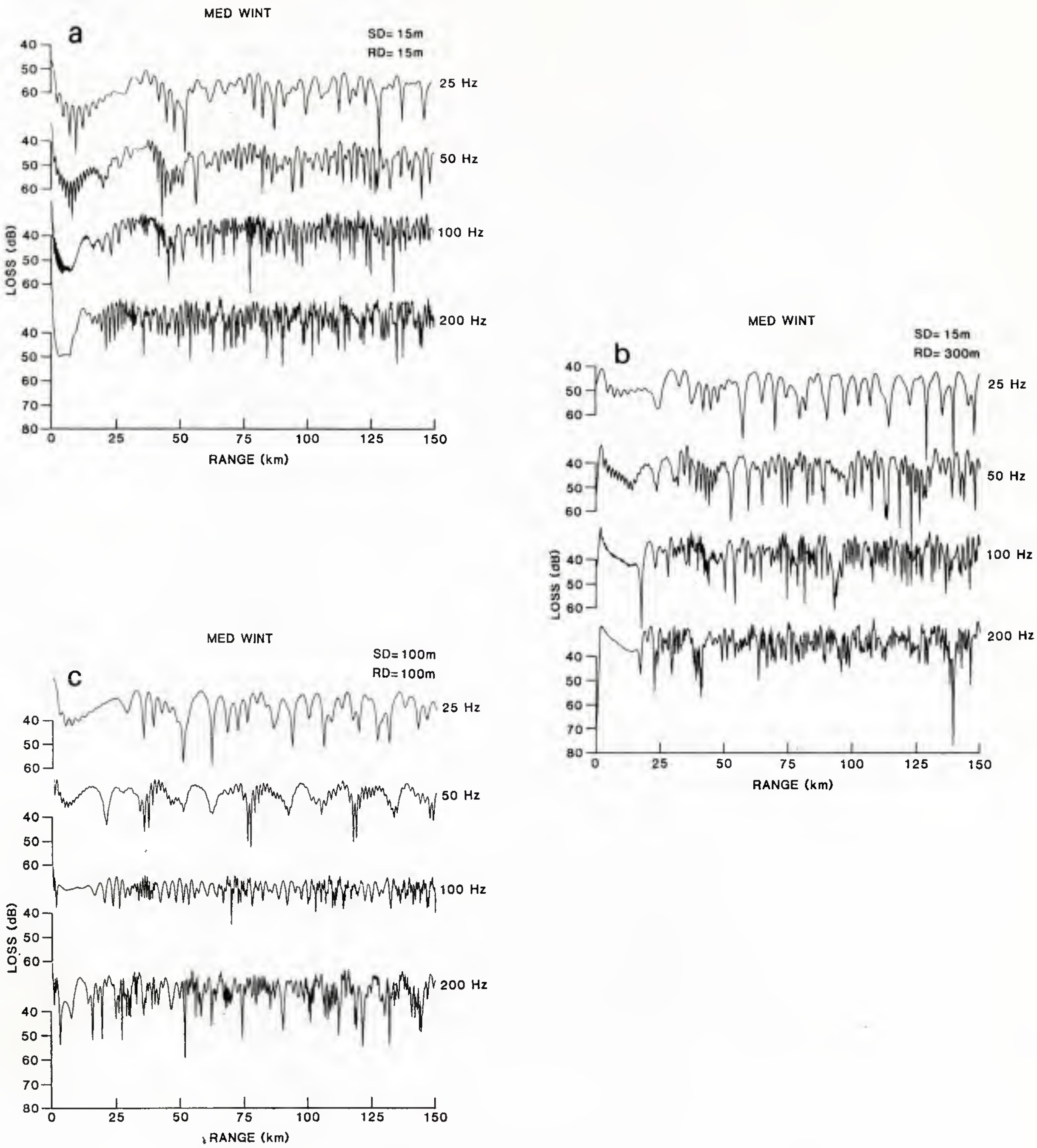

Fig. II-4: Transmission loss versus range at selected frequencies for Mediterranean winter profile: (a) SD = 15 m, RD = 15 m; (b) SD = 15 m, RD = 300 m; (c) SD = 100 m, RD = 100 m.

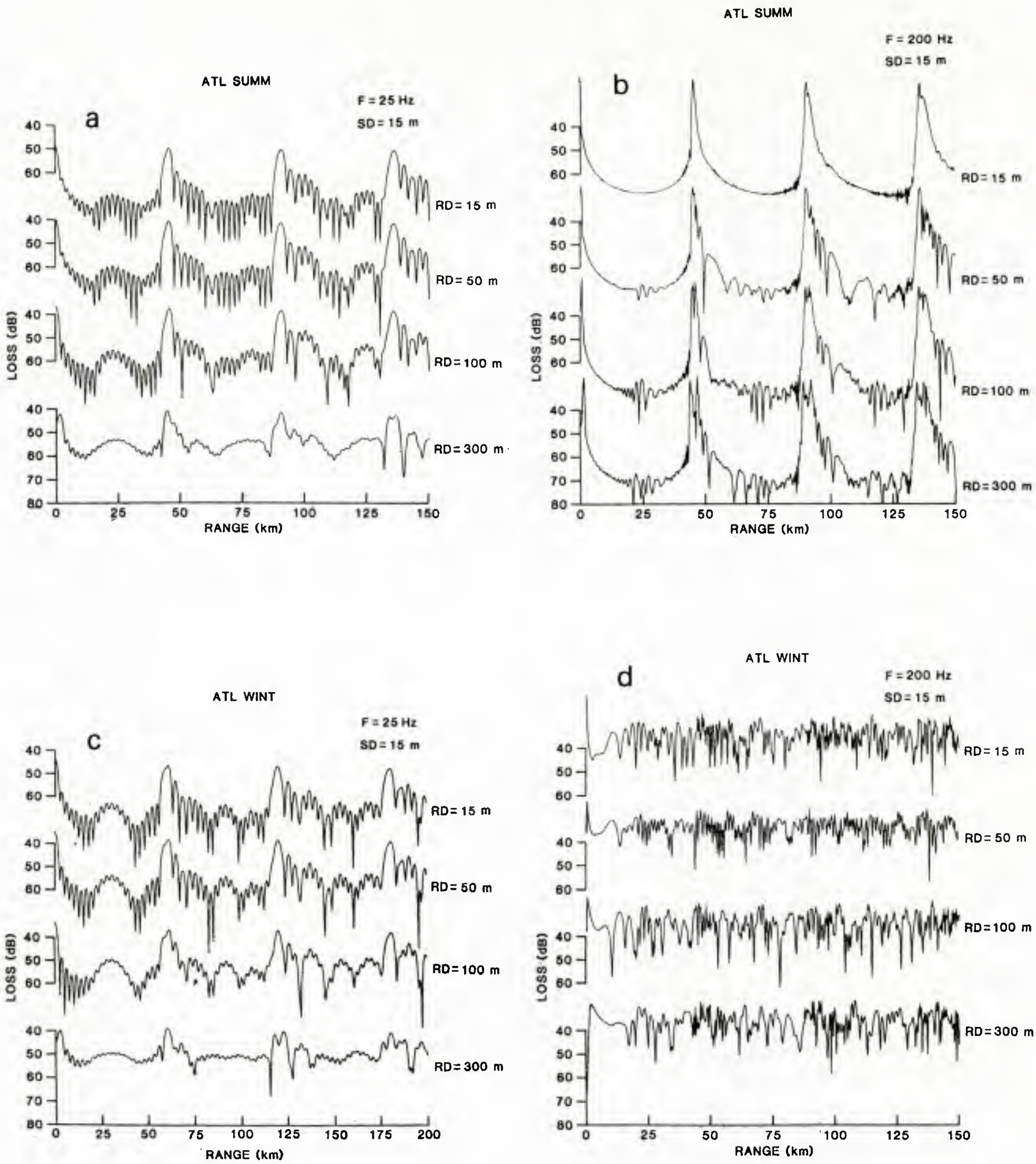

Fig. III-1: Transmission loss versus range at selected receiver depths for Atlantic profiles: (a) summer, $F = 25$ Hz, SD = 15 m; (b) summer, $F = 200$ Hz, SD = 15 m; (c) winter, $F = 25$ Hz, SD = 15 m; (d) winter, $F = 200$ Hz, SD = 15 m.

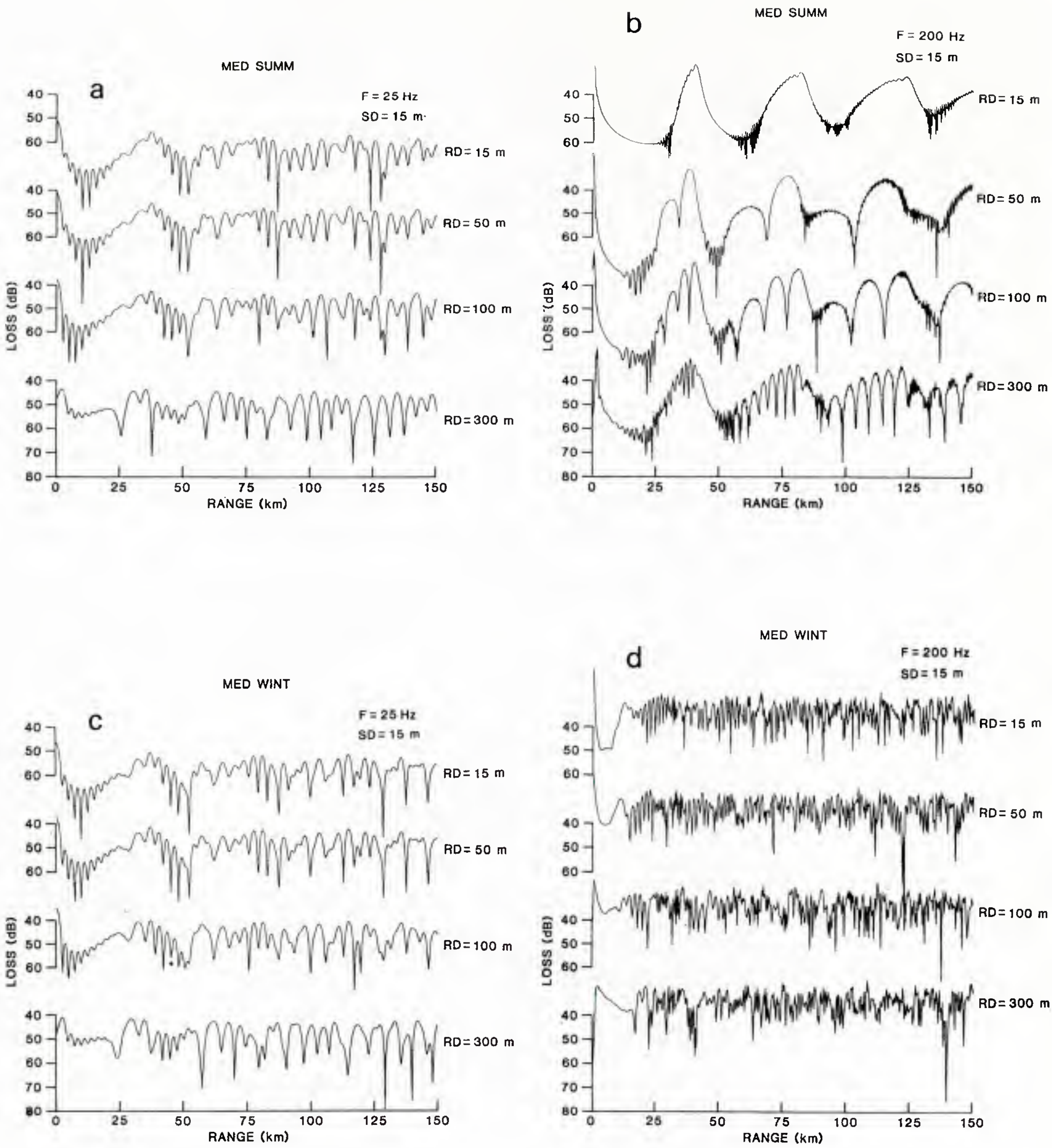

Fig. III-2: Transmission loss versus range at selected receiver depths for Mediterranean profiles: (a) summer, $F = 25$ Hz, SD = 15 m; (b) summer, $F = 200$ Hz, SD = 15 m; (c) winter, $F = 25$ Hz, SD = 15 m; (d) winter, $F = 200$ Hz, SD = 15 m.

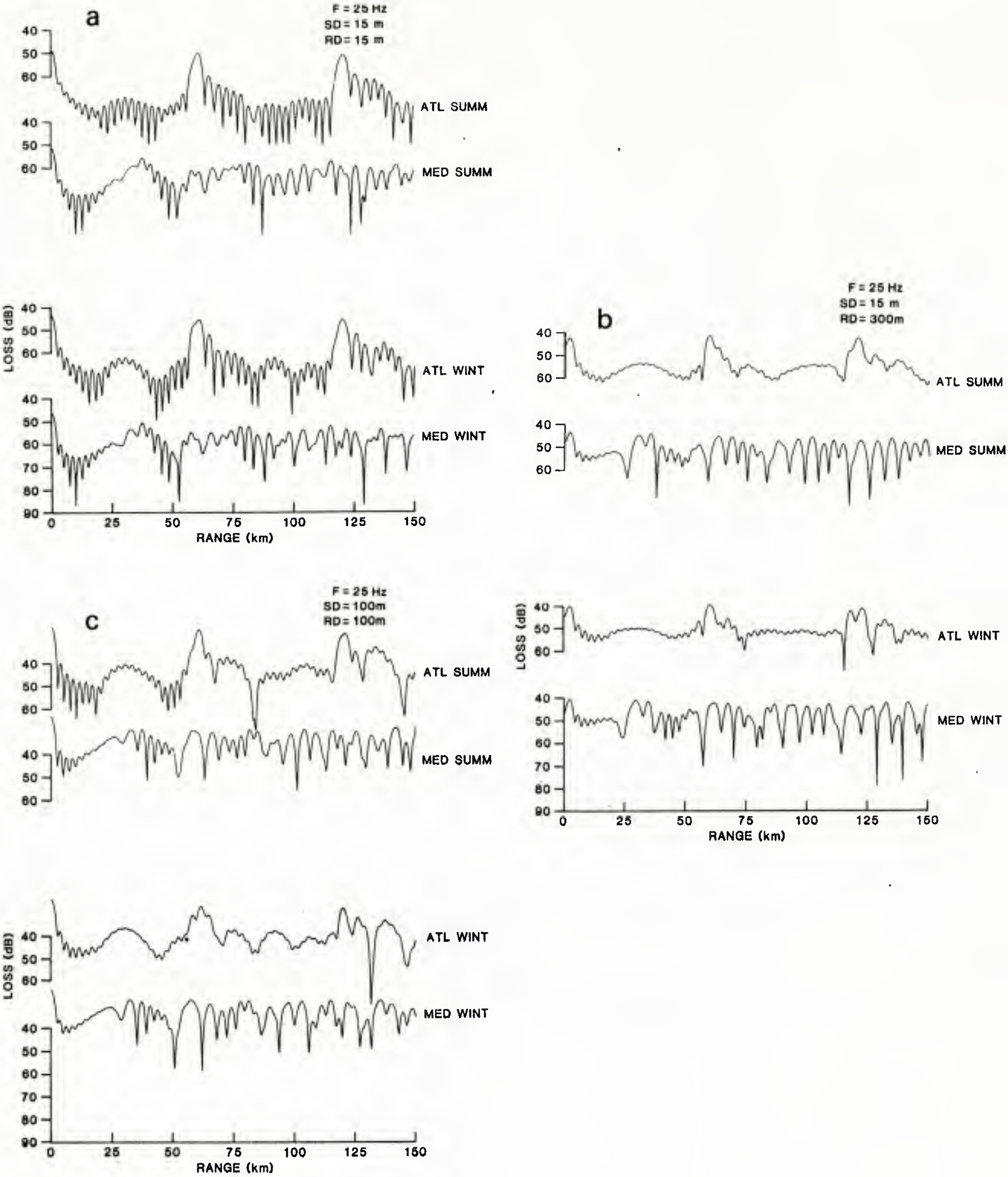

Fig. IV-1: Transmission loss versus range for Atlantic and Mediterranean summer and winter profiles at $F = 25$ Hz: (a) SD = 15 m, RD = 15 m; (b) SD = 15 m, RD = 300 m; (c) SD = 100 m, RD = 100 m.

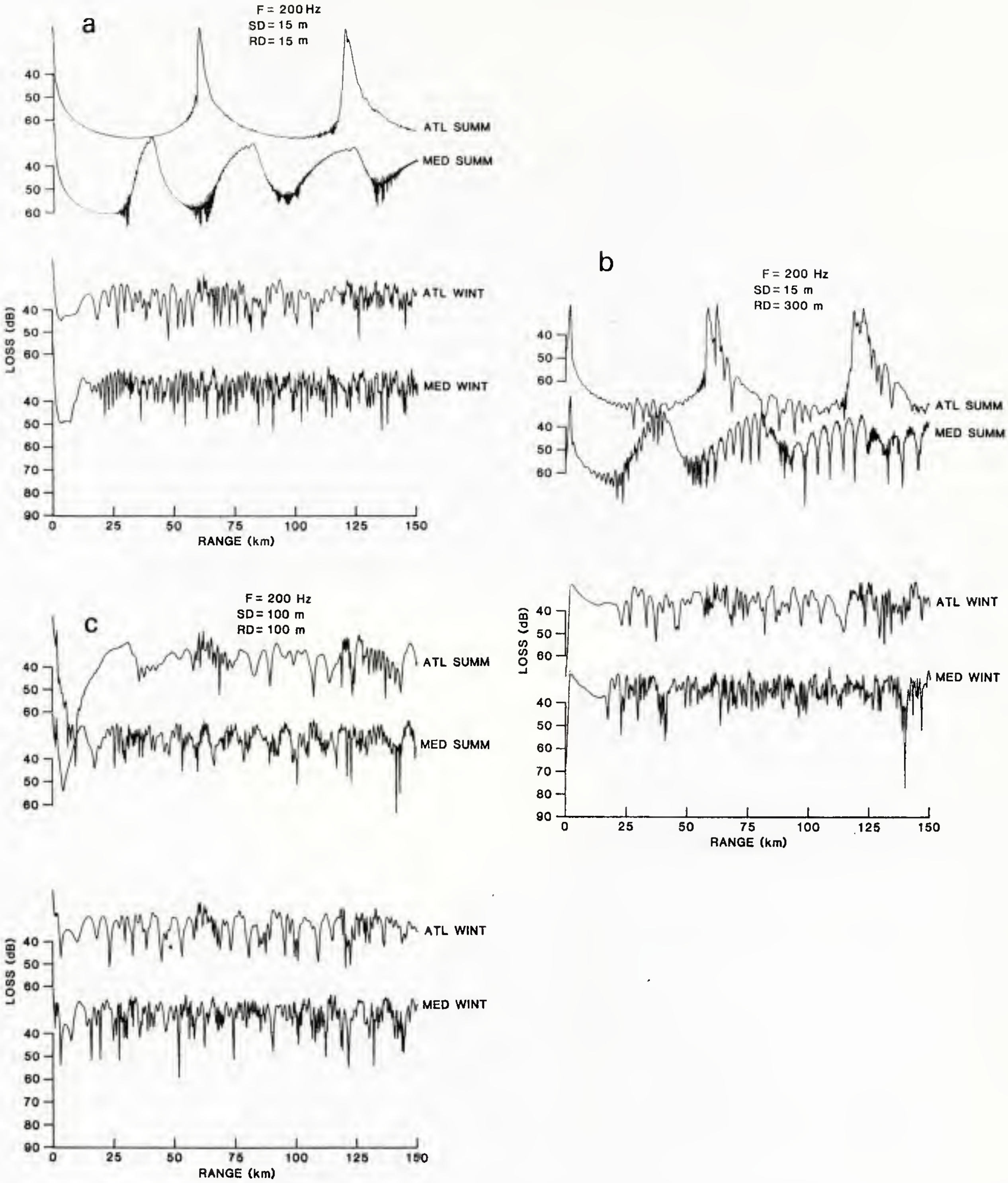

Fig. IV-2: Transmission loss versus range for Atlantic and Mediterranean summer and winter profiles at $F = 200$ Hz: (a) SD = 15 m, RD = 15 m; (b) SD = 15 m, RD = 300 m; (c) SD = 100 m, RD = 100 m.

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